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I. C. 6399

FEBRUARY, 1931

DEPARTMENT OF COMMERCE

UNITED STATES BUREAU OF MINES
SCOTT TURNER, DIRECTOR

INFORMATION CIRCULAR

CONSTRUCTION OF THE WACHUSETT-COLDBROOK TUNNELS

BY

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CONSTRUCTION OF THE WACHUSETT-COLDBROOK TUNNELS[1]

By Douglas C. Corner[2]

INTRODUCTION

This is the first of a series of papers dealing with modern tunnel-driving methods, compiled in accordance with an outline prepared by engineers of the United States Bureau of Mines and to be published in a series of information circulars by the bureau. This series will supplement a similar and earlier series of papers dealing with mining methods and costs.

ACKNOWLEDGMENTS

The author desires to express his appreciation of the assistance of A. C. Dennis, manager for the West Construction Co. Contractors, and Frank E. Winsor, chief engineer for the Boston Metropolitan District Water Supply Commission who furnished much of the data and detailed description of operation appearing in the following pages. C. F. Jackson, mining engineer, United States Bureau of Mines, collaborated in the preparation and arrangement of the text.

GENERAL NOTES

This report covers some of the practices in construction of 14 miles of the Wachusett-Coldbrook Tunnel, for the purpose of diverting additional water into the Wachusett reservoir, from which the metropolitan district of Boston receives its water supply. The construction period was long enough to permit the rate of construction to be at an economic speed. The tunnel section has a curved top, straight sides, and slightly curved invert. The shape and size are as shown in figures 1 and 2, and required the removal of 6.79 cubic yards per linear foot. The tunnel was driven from eight shafts, being about 200 feet below the hydraulic grade. The deepest shaft was over 600 feet deep, The number of shafts was in excess of the economic requirement. Gradients were generally level, or nearly so, but there were sections where the grade was 3 feet per hundred. The tunnel elevation was designed to be low enough to be in rock at all points. Numerous drillings were made to determine rock surface and some drilling into the rock was done. Figure 3 is a key plan and profile of the tunnel.

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[1] The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from U. S. Bureau of Mines Information Circular 6399."

[2] One of the consulting engineers, U. S. Bureau of Mines.

GEOLOGY

The rock was for the most part sedimentary, with about 4 miles of granite. The sedimentary rock was fairly hard and required very little timbering. The bedding planes were horizontal and generally unbroken. The breaking of the rock varied from good to hard breaking, depending upon whether cross slips were present or not. This rock drilled readily. Water seams carrying over 1,000 gallons per minute were cut occasionally. The granite was generally hard to drill and hard to break, except the small portions which had crossed cracks. The granite was generally dry, but some water seams carrying over 1,000 gallons per minute were cut. Generally the water from the seams, both in the sedimentary and granite rock, decreased in volume after being opened, and some of the seams almost dried up.

About a mile of tunnel in the sedimentary rock began to scale when exposed to the air. As an alternative to timbering this section, which would otherwise have been necessary, gunniting was tried and proved successful in holding this particular kind of ground and was much cheaper than timbering.

PREPARATION

Camps were built of the present-day standard type. Electric-driven compressors in three units amounting to about 2,000 cubic feet per minute, total capacity were placed at each shaft. Electric hoists, high pressure blowers, power shovels, and storage-battery locomotives were used.

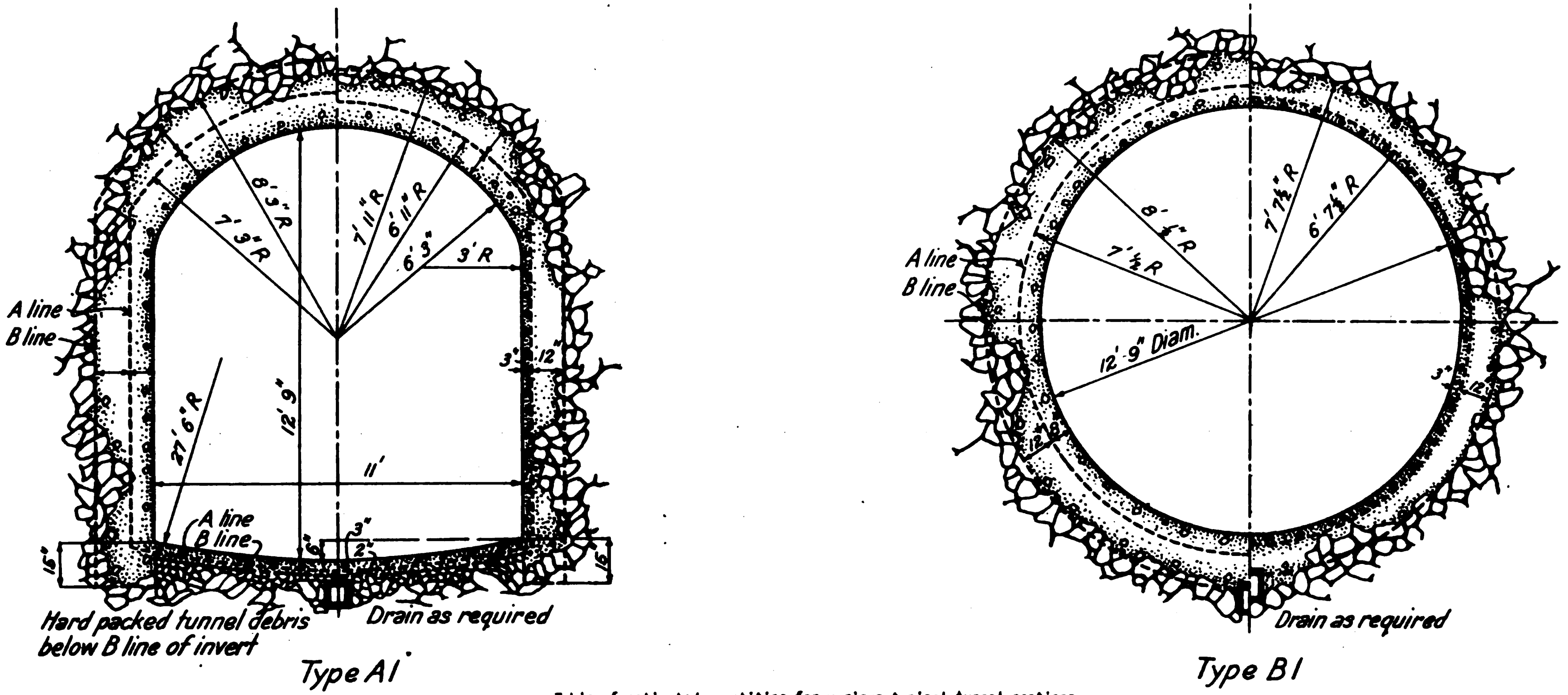
METHOD OF PROCEDURE

General Method.- The tunnel driving was all done from shafts and usually the full face was excavated. One heading was drilled while the opposite one was being mucked, the drill crew employing a drill carriage to set up in a clean heading. Shifts worked eight hours and changed at their working face. Four hours was the general minimum time for a round, while the average was about 6½ hours. When one end was flooded or for any other reason could not be worked, the drill crew replaced the mucking crew, doing the mucking after having blasted their round.

Some headings were worked by the heading and bench method on two 10-hour shifts per day in each heading and employed air-operated shovels or hand-loading. Three 8-hour shifts with the full face method and using a drill carriage and loading with electric power shovel advanced more than four 10-hour shifts by the heading and bench method, however.

Drill Carriage.- Drill carriages were built on the job. When taken down they could be side-tracked out of the way of other equipment. When moved to the face, staging on the carriage could be quickly extended to the width of the tunnel and 8 feet ahead to reach the face. This staging was supported entirely by the carriage and formed a working platform for setting up and drilling from the upper cross bar. The lower cross bar was set up and operated from the tunnel floor.

The drill carriage provided space for storing staging when taken down, also for blocking and wedges, hand tools, oil, drill steel, regular and spare bars, and drill machines. The carriage had a system of fixed air and water manifolds to which short individual hose for connection to machines were permanently



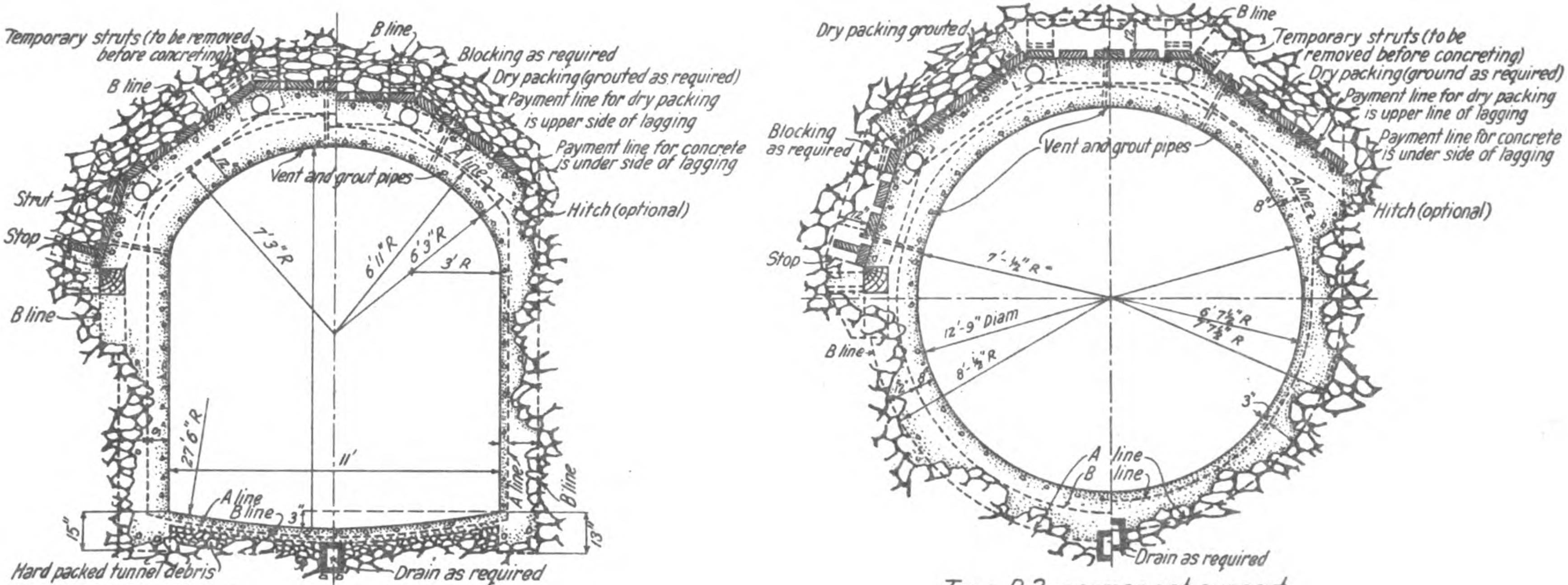
Type A1

Type B1

Table of estimated quantities for various typical tunnel sections
(Approximate quantities per linear foot of tunnel)

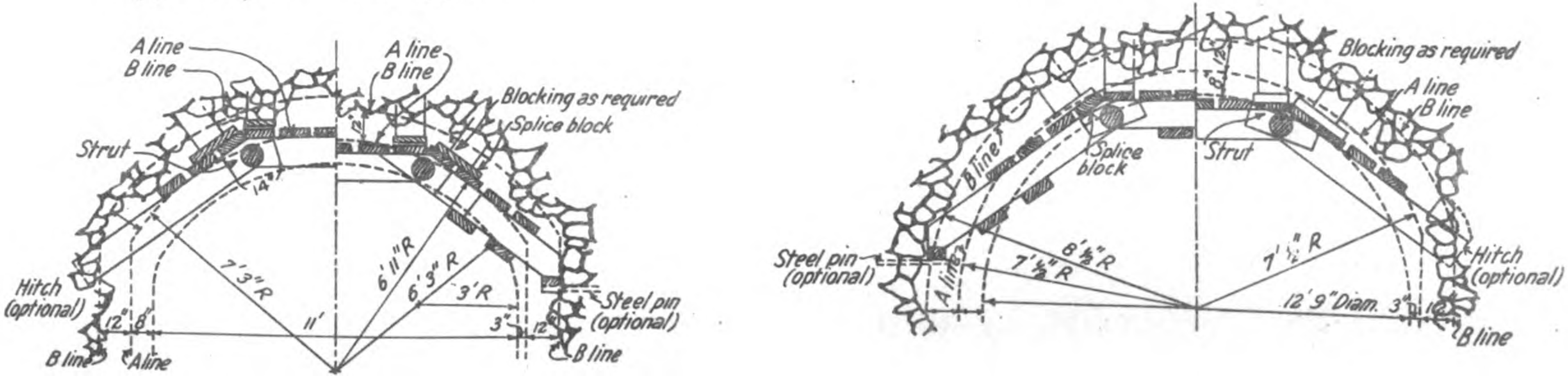
Item	Unit	Type A1		Type B1		Type A2		Type A3		Type B2		Type B3	
		3" to A line	8" to A line	3" to A line	8" to A line	3" to A line	8" to A line	3" to A line	8" to A line	3" to A line	8" to A line	3" to A line	8" to A line
Excavation	Cu. ft.	6.79	7.35	6.75	7.50	7.48	8.75	6.79	7.35	7.94	8.75	7.12	7.50
Concrete in side walls	- -	.87	1.14	—	—	.87	1.14	.87	1.14	—	—	—	—
Concrete in arch	- -	1.05	1.33	—	—	1.04	1.37	1.05	1.33	—	—	—	—
Concrete in invert	- -	.17	.17	—	—	.17	.17	.17	.17	—	—		
Concrete, total	- -	2.09	2.64	2.04	2.80	2.08	2.68	2.09	2.64	2.40	2.74	2.37	2.80
Dry packing	- -	—	—	—	—	.57	.84	—	—	.65	.90	—	—

Figure 1.- Typical tunnel sections, Wachusett-Coldbrook tunnel


Temporary struts (to be removed before concreting)
B line
B line
Blocking as required
Dry packing (grouted as required)
Payment line for dry packing is upper side of lagging
Payment line for concrete is under side of lagging
Vent and grout pipes
A line
Hitch (optional)
Strut
Stop
B line
7'3"R
6'11"R
6'3"R
3'R
27'6"R
11'
A line
B line
3"
A line
B line
15"
13"
Hard packed tunnel debris
Drain as required
Dry packing grouted
B line
Temporary struts (to be removed before concreting)
Dry packing (ground as required)
Payment line for dry packing is upper line of lagging
Payment line for concrete is under side of lagging
Blocking as required
Vent and grout pipes
A line
8"
Hitch (optional)
Stop
7'-½"R
12'-9" Diam
6'7½"R
7'7½"R
8'-½"R
B line
3"
A line
B line
Drain as required

Type A2, permanent support

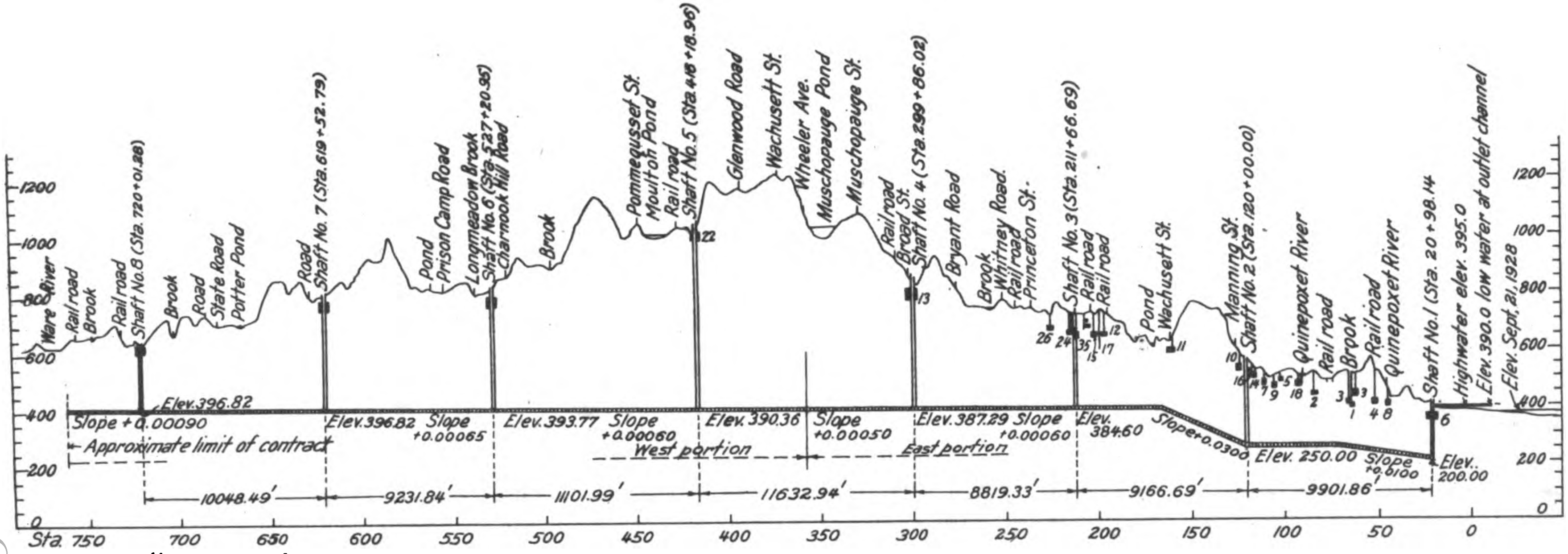
Type B2, permanent support



Type A3, temporary support

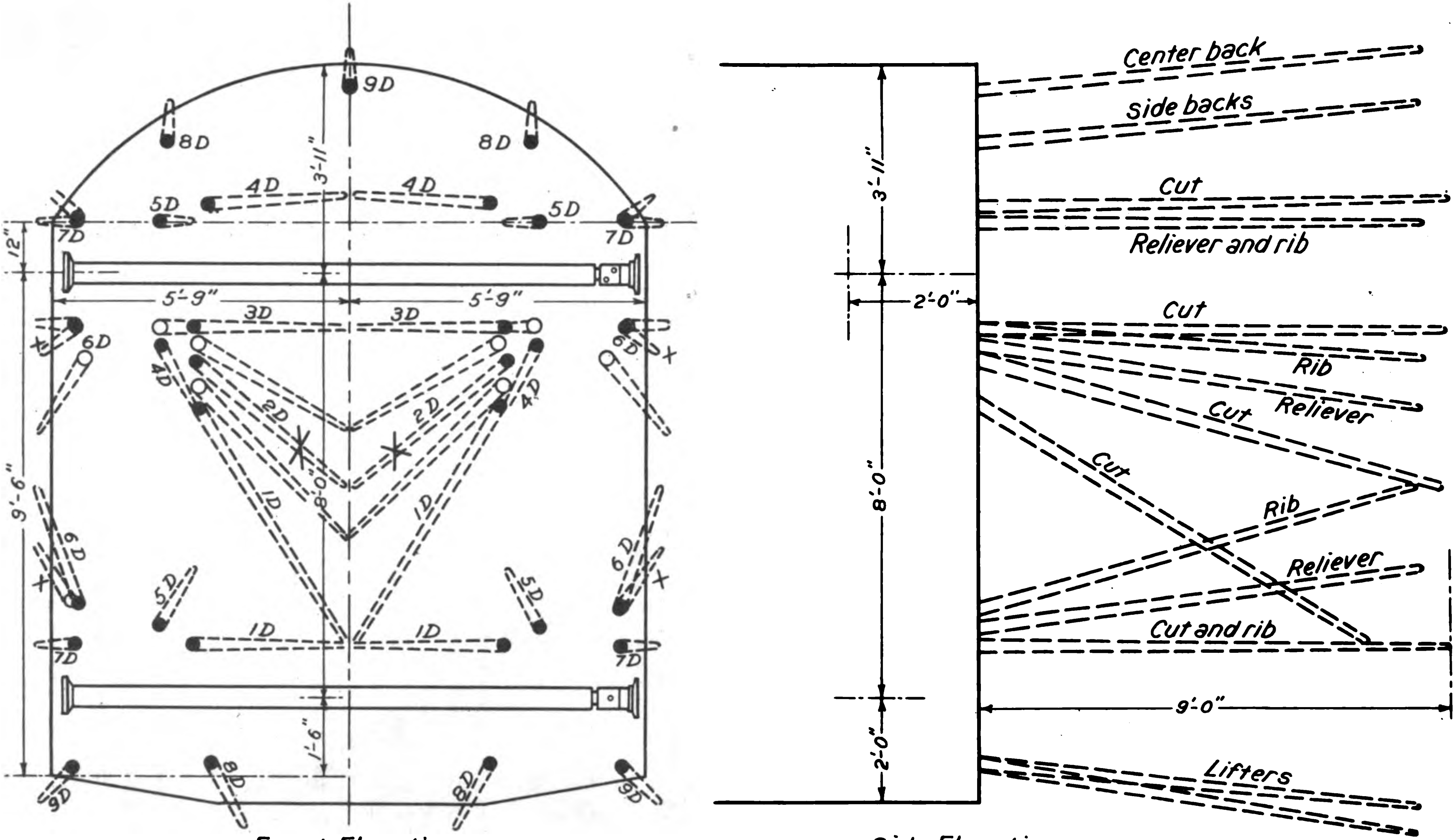
Type B3, temporary support.

Figure 2,- Typical timbered tunnel section, Wachusett-Coldbrook tunnel



Note-*Elevations Boston city base*

Figure 3.- Profile of Wachusett-Coldbrook tunnel



Front Elevation

Side Elevation

Figure 4.- WACHUSETT-COLDBROOK tunnel round

● — Minimum 31-hole round for good rock
○ — Usual round, 37-holes. X-holes omitted
Numbers 1D-2D, etc., indicate delay exploder numbers

attached. Fifty-foot lengths of large water and air hose connected the pipe system on the drill carriage to the water and air mains back of the face. The large hose was also stored on the drill carriage when it was moved back. It took 15 to 25 minutes to start drilling after the carriage arrived at the face.

Drilling.- A minimum of 31 holes per round, drilled by five machines, was used in good breaking ground, as shown in Figure 4 herewith. Generally, however, each of the machines on the upper bar drilled two additional holes. The side machines each drilled another reliever and rib hole, changing the pointing of those shown so as to get equal spacing, including the extra hole. The center machine drilled an extra pair of cut holes spaced equally. The two machines on the lower bar drilled no extra holes but modified the pointing to conform to spacing for extra rib and reliever holes drilled by the upper machines. The shift foreman was responsible for the number and pointing of the drill holes.

Rounds with "baby cuts" or "kickers" and diamond cuts with the cut looking up from the lower bar to meet the cut under the upper bar were experimented with and abandoned. It appeared that the advantage of a better break was outweighed by the mucking delay and pipe damage from fly-rocks.

Blasting.- Blowing out and loading top holes was done before taking down staging, and the lights were taken back from the face before loading started. Explosive used was 40 per cent low-freezing gelatin dynamite and occasionally 60 per cent in sticks 1½ by 12 inch sticks. One stick was put in each hole before the primer, and five to seven boxes was the usual charge. The usual break was 7 feet. New-type Atlas electric delay with No. 8 cap was used and was entirely satisfactory, eliminating misfires, delayed holes, burnt holes, and out-of-sequence firing. Hook-up was in parallel and the firing line carried 440 volts. Disconnection of firing line to be plugged in when ready to fire was the practice after the current passed two open firing boxes during a severe thunderstorm.

Mucking.- Most of the mucking was done by electric power shovels. One shovel was supplied for each heading and one spare shovel and turntable were provided for each pair of headings. Three-yard, box-body, side-dump cars were used which were handled by storage-battery locomotives. The locomotives pulled the empty cars to the face where an overhead air hoist car transfer was used without any track switch near the face. The locomotive left the empty cars near the car hoist and coupled to the load behind the shovel, backing up with this load beyond the car hoist where one of the empties just brought in has been pushed up by hand, raised by air hoist, and pushed over against the rib so as to clear the locomotive and load coming out. When the locomotive passed the air hoist the suspended empty was set on the track and pushed up to the shovel ahead of the car previously loaded. Figure 5 shows the arrangement for passing cars.

Loading out a 7-foot round required from three to seven hours, depending largely upon the amount of water at the heading, and whether reblasting is required, etc. An experienced miner was with the mucking crew to do any necessary reblasting and to do the scaling. The shovel operator and scaler spotted the line and grade at the face from lights hung from engineers measurements and from this point layed off and painted the standard section on the face as a guide for the drill shift to follow.

Shafts.- The round shaft on the center line of the tunnel which seems to be the universal type of shaft in the east, was used. This type of shaft is more expensive to construct and to operate and has less capacity for tunneling operations than the rectangular offset shaft used on western construction. The round shaft is necessary where water is received into or supplied from the tunnel under high pressure.

Drainage.- Centrifugal pumps were used to pump water up the shaft from a sump near the foot of the shaft. At the start of operations, piston pumps were used in the headings. However, the unexpected volume of water cut was sometimes over 1,000 gallons per minute, so that the installation of sumps and centrifugal pumps for the heading water became necessary. Water was the cause of great expense and delay and at times flooded the down hill or "dip" headings and threatened the loss of shafts 2, 3, and 4 by flooding.

Ventilation.- Ventilation was by exhausting only, by means of Root blowers driven by 60-hp. motors through 14-inch wooden pipe hung along the rib. The wooden pipe stands more hard service than metal pipe and the joints are tight even when not laid straight.

Labor.- The drilling crew consisted of a shift boss, five machine men, five helpers, one trimmer, and one nipper. The mucking crew consisted of shovel operator, scaler, cable tender, mucker, two air hoistmen at car transfer, two locomotive runners, and an oiler overhauling the idle shovel. There were one to three pumpmen per shift. The hoisting crew consisted of two bottom-cage men, two topmen, one locomotive runner for the dump train, one dumpman, hoisting engineer, and oiler. The above for each of three shifts.

The indirect labor was about as follows: Superintendent, assistant superintendent, master mechanic, two mechanic's helpers, electrician, electrician's helper, timekeeper, powderman, labor foreman, and four or five laborers, and two steel sharpeners with two helpers. To this may be added an average of one truck driver and two laborers freighting supplies.

Progress.- The normal progress was four 7-foot rounds one day and five rounds the next day. The monthly rate often exceeded 900 feet. The minimum time for drilling and blasting a round was under four hours and the minimum time for mucking a round was under three hours. The mucking crew was delayed about 30 minutes of each round by having to wait for the gas to clear from the heading, and sometimes an additional delay was occasioned for reblasting. The drill crew had no delay for ventilation. Water caused greater delay to the mucking than to the drilling.

Costs.- Costs were made high by two natural causes - hard-breaking rock and abnormal flow of water. But the fact that the design of the shafts is expensive and the number is in excess of the economic requirement, together with the expense of compliance with arbitrary requirements imposed by political and labor union officials, has added about 40 per cent to the cost of like work free from these disadvantages.

Concreting.- The entire tunnel is to be concrete lined. Quantity of concrete is about 2 cubic yards per linear foot. Tunnel rock is being crushed for both stone and sand aggregate. The material is taken into the tunnel dry, then is mixed and dumped directly into a concrete gun. The concrete plant was designed by W. F. Webb, and is believed to be a distinct advance in this rapidly progressing art.

Average cost per linear foot of tunnel excavation from typical shafts as figured prior to final cost adjustments

	Shaft A[1]	Shaft B[2]	Shaft C[3]
Plant, camp, etc.	$15.64	$12.25	$10.18
Overhead	4.00	3.01	3.05
Power	4.73	4.36	6.13
Material and supplies	19.72	16.42	19.00
Labor	32.71	30.34	34.85
Total	76.80	66.38	73.21

1 Shaft A - Granite rock, very wet.
2 Shaft B - Sedimentary rock, very dry.
3 Shaft C - Sedimentary rock, like B, except very wet.

The rough conclusion to be drawn from above and other data concerning the cost per linear foot of a 6.79 cubic yard tunnel in good sedimentary rock is as follows:

Plant, overhead, etc.	$15.00
Operating cost, of excavation	40.00
Additional very wet heading	7.00
Additional dry granite rock	3.50
Additional for shaft operation, over adit or portal	11.00
Total	$76.50

Final costs per foot of Wachusetts-Coldbrook tunnels

Feet	Labor	Power	Material and supplies	Overhead	Total operating cost	Investment	Total cost	[illegible]-mated cost
No. 2 shaft tunnels								
12,276	$32.60	$4.95	$19.75	$4.10	$61.40	$15.85	$77.25	$76.35
No. 4 shaft tunnels								
10,576	32.95	5.50	23.45	3.80	65.70	17.00	82.70	77.25
No. 5 shaft tunnels								
10,778	30.50	4.40	15.60	2.10	52.60	12.30	64.90	75.60
No. 6 shaft tunnels								
8,157	40.75	4.60	16.25	2.45	64.05	14.70	78.75	76.60
No. 7 shaft tunnels								
8,029	33.95	6.85	17.10	2.80	60.70	11.20	71.90	75.65
No. 8 shaft tunnels								
8,810	35.20	5.95	19.05	2.55	62.75	10.00	72.75	84.55
Total 58,626	- -	- -	- -	- -	- -	- -	- -	- -
Average	34.00	5.30	18.70	3.05	61.05	13.70	74.75	77.55

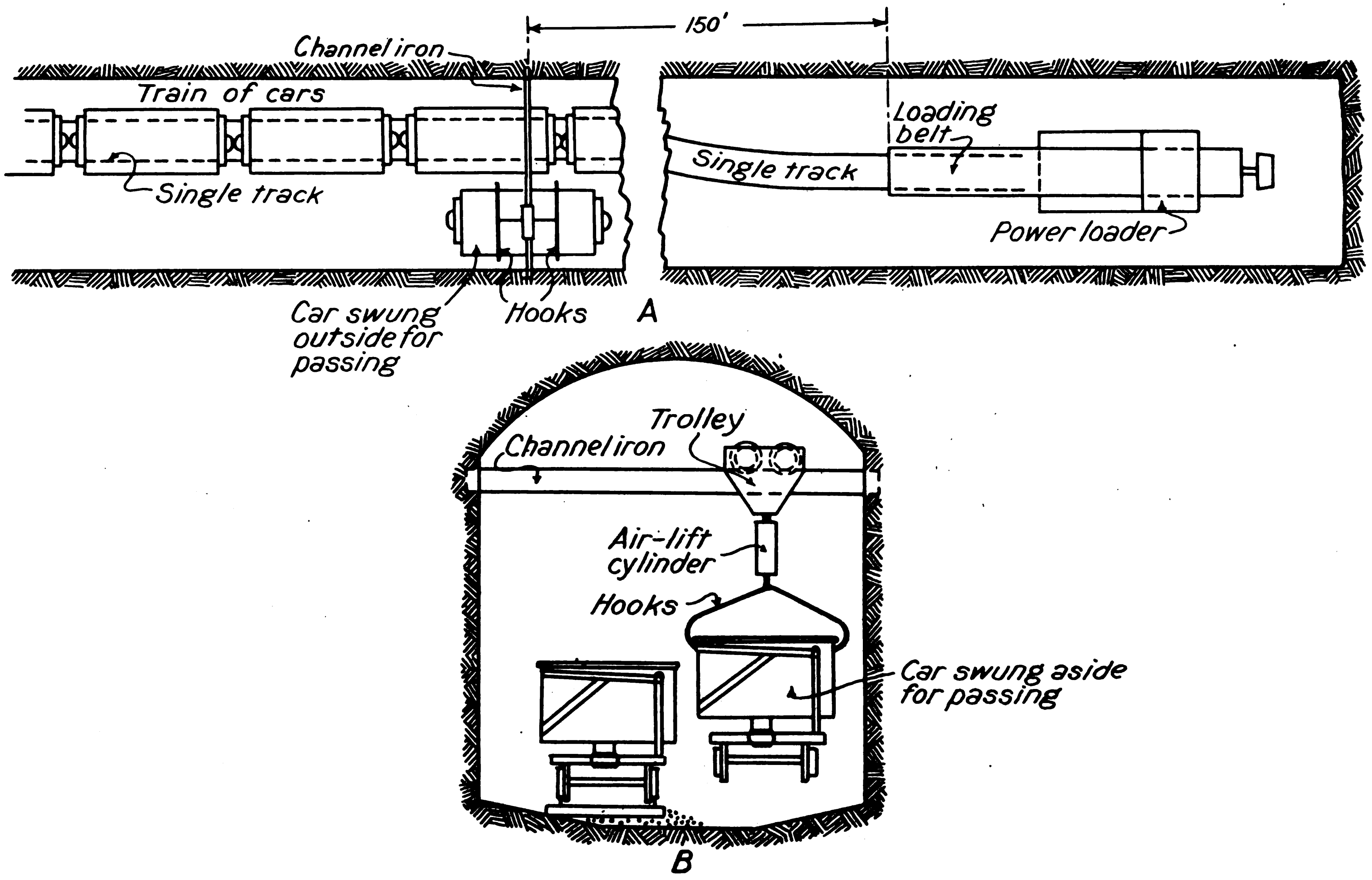


Figure 5.-Diagrammatic sketch showing method of passing cars behind power loader. A. Plan. B. Transverse section